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G2F FCW F23E F28W

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INT CL[6] G02F
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(54) **Optical modulator**

(57) The device comprises a quantum well guide region 57 for transmission of an optical beam therethrough, front 61 and back 53 gates an ohmic contact 63 to the guide region and a substrate, the guide region 53 comprises a quantum well is interposed between the front and back gates. Applying biases to the front and back gates allows modulation of an incident beam in the guide region by varying the carrier concentration and the electrical field in the guide region.

A single gate embodiment is also possible if a doped layer is provided at the other side of the quantum well to the single gate. A patterned back gate (53, figure 9) provides a variation in the thickness of the cladding below the quantum well and provides lateral optical confinement.

FIG.7

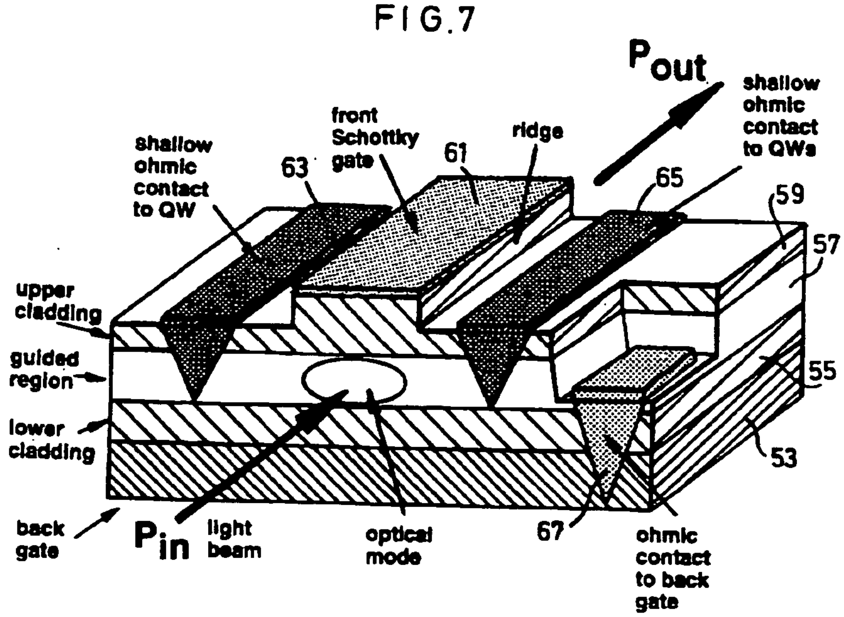

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FIG.1

Single gated structures

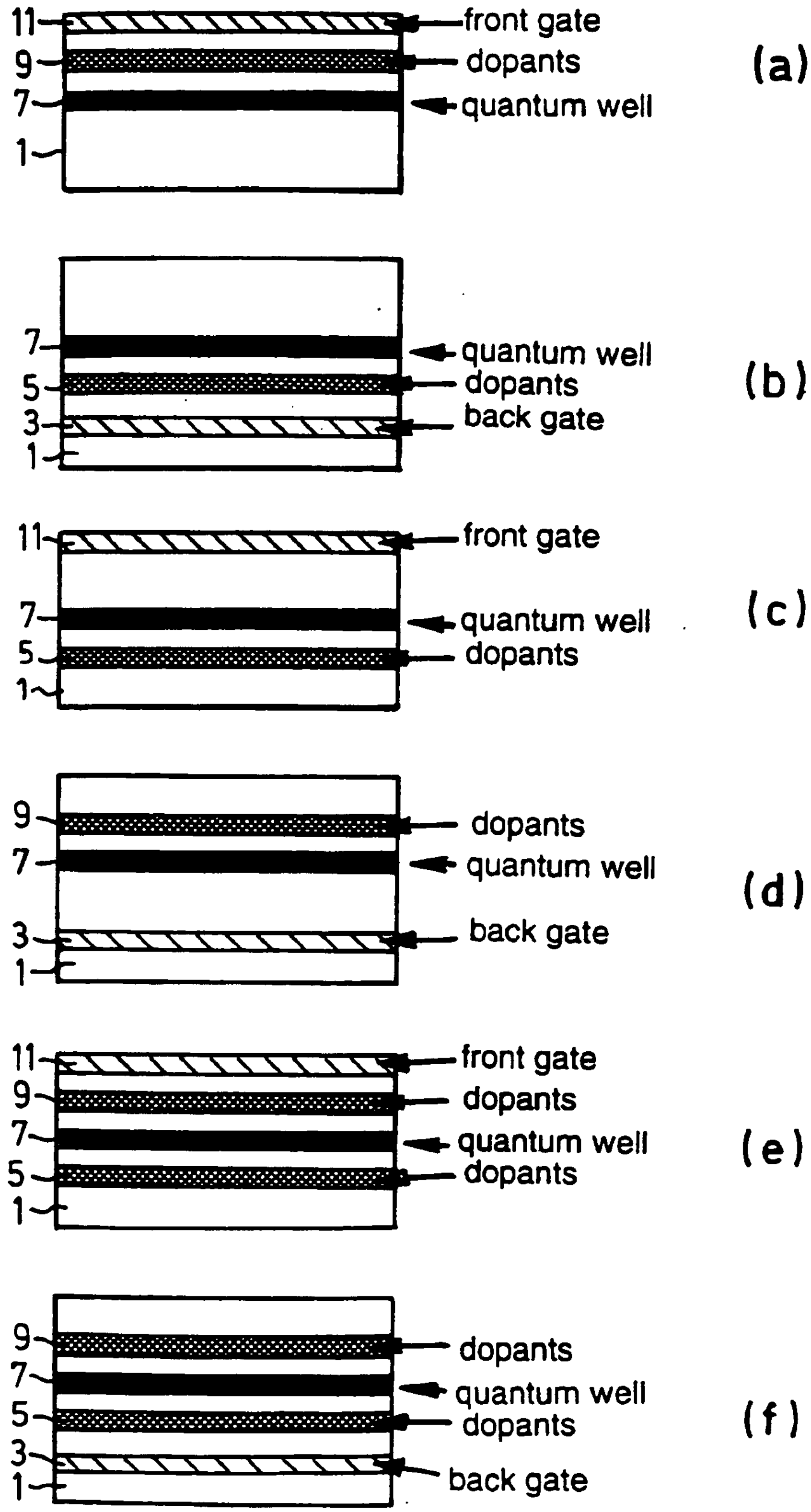


FIG. 2

Double gated structures

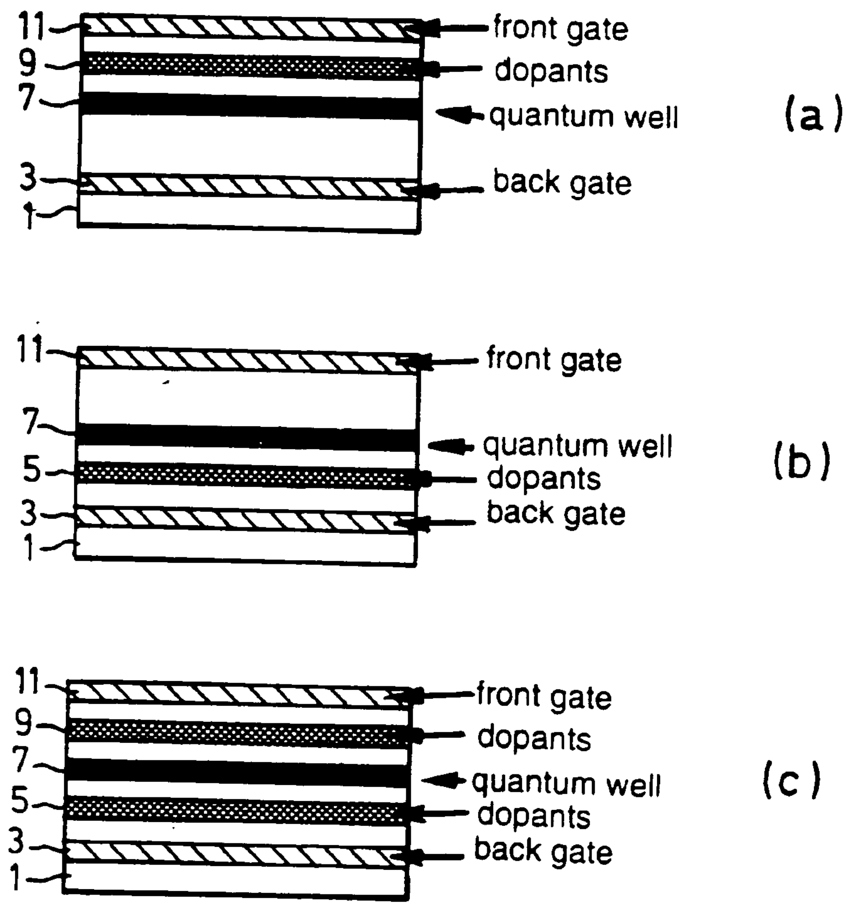


FIG. 3

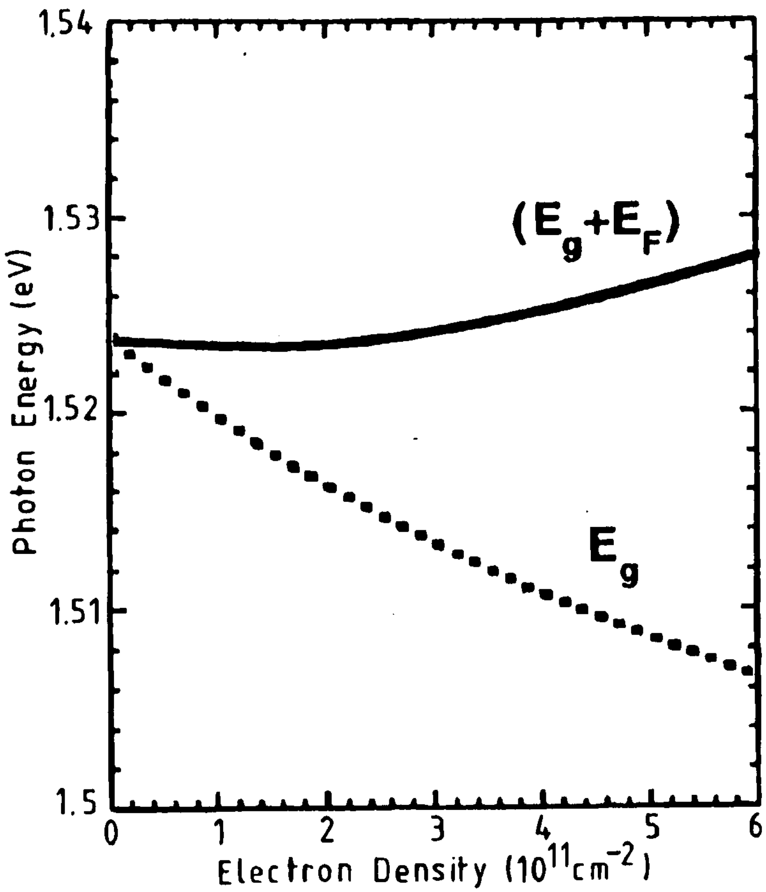

1.54
1.53
1.52
1.51
1.5
Photon Energy (eV)
0
1
2
3
4
5
6
Electron Density ($10^{11}cm^{-2}$)
(E_g+E_F)
E_g

FIG. 4

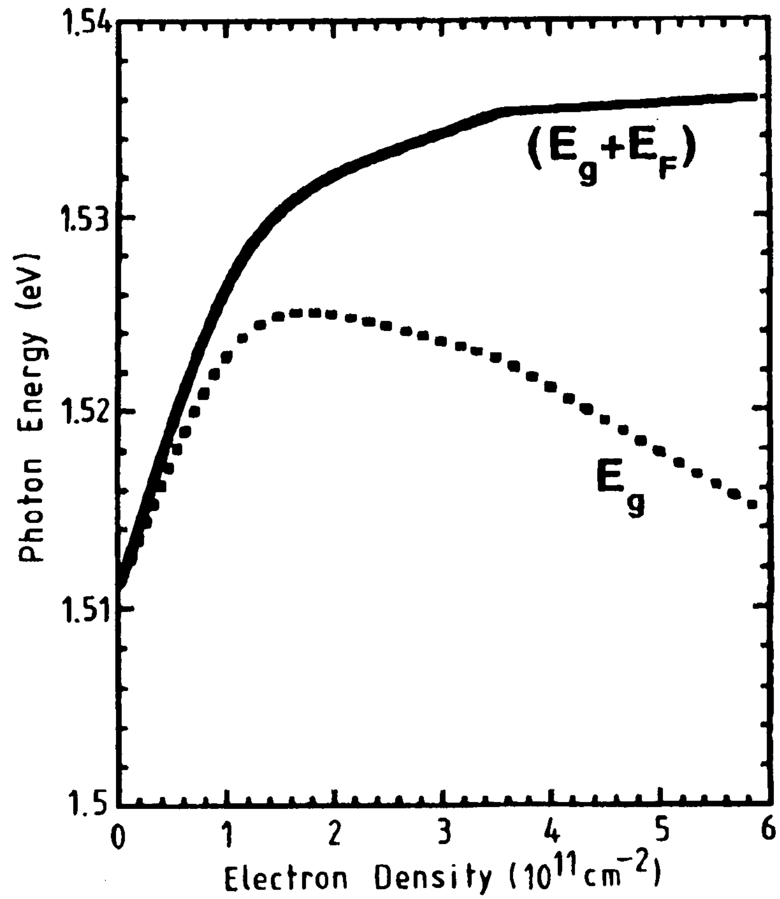

1.54
1.53
1.52
1.51
1.5
Photon Energy (eV)
0
1
2
3
4
5
6
Electron Density ($10^{11}cm^{-2}$)
(E_g+E_F)
E_g

FIG 5

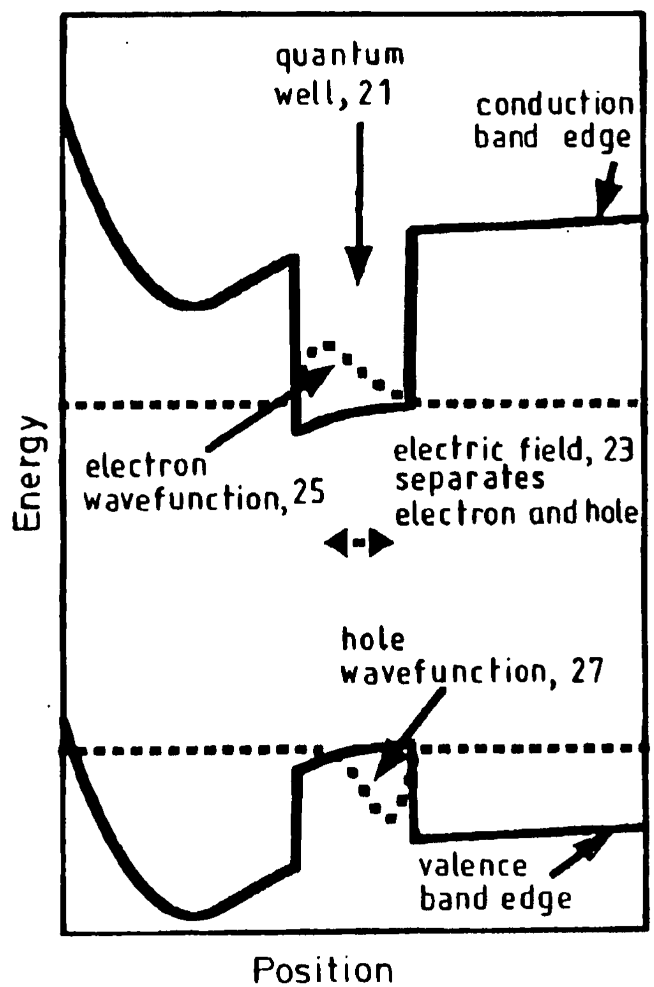

quantum
well, 21
conduction
band edge
electron
wavefunction, 25
electric field, 23
separates
electron and hole
hole
wavefunction, 27
valence
band edge
Energy
Position

FIG.6

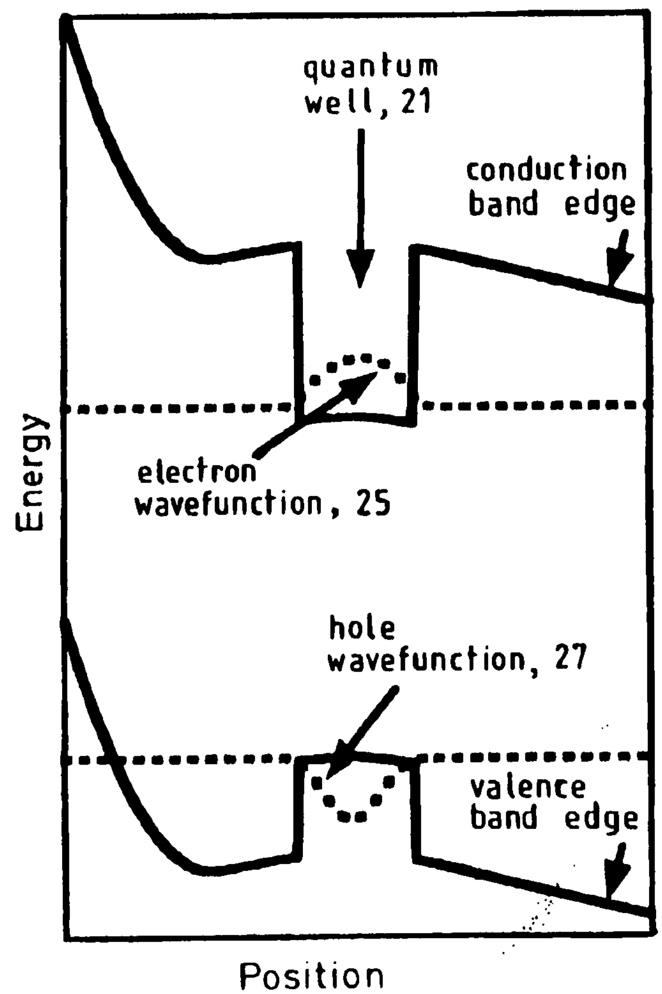

quantum
well, 21
conduction
band edge
electron
wavefunction, 25
hole
wavefunction, 27
valence
band edge
Energy
Position

FIG.7

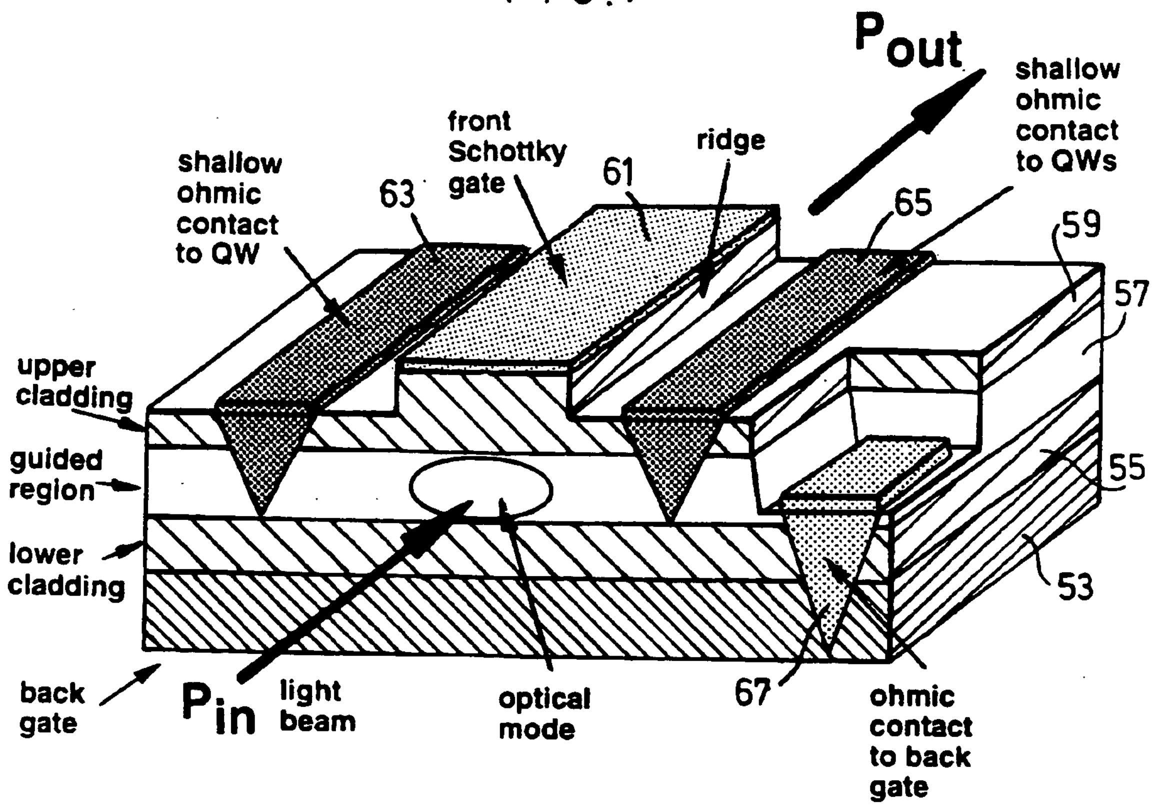


FIG.8

Detail of guided region

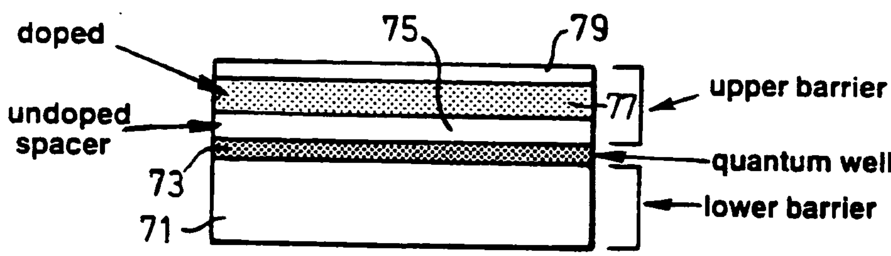


FIG.9

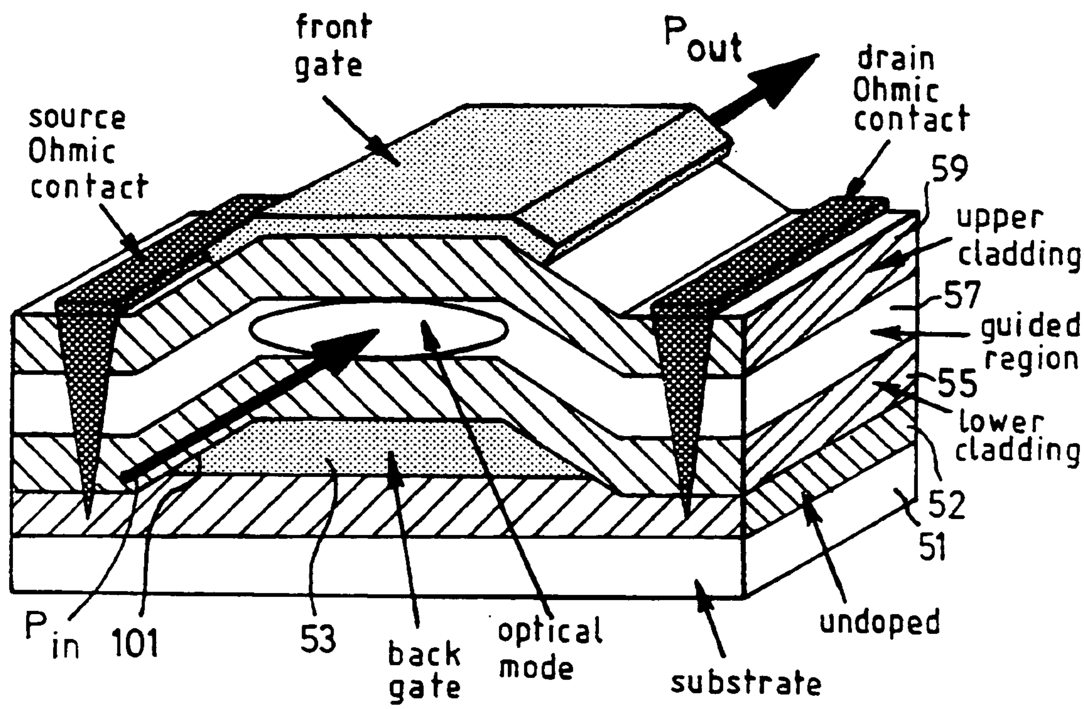

front gate
P out
drain Ohmic contact
source Ohmic contact
59
upper cladding
57
guided region
55
lower cladding
52
51
undoped
P in
101
53
back gate
optical mode
substrate

FIG. 10

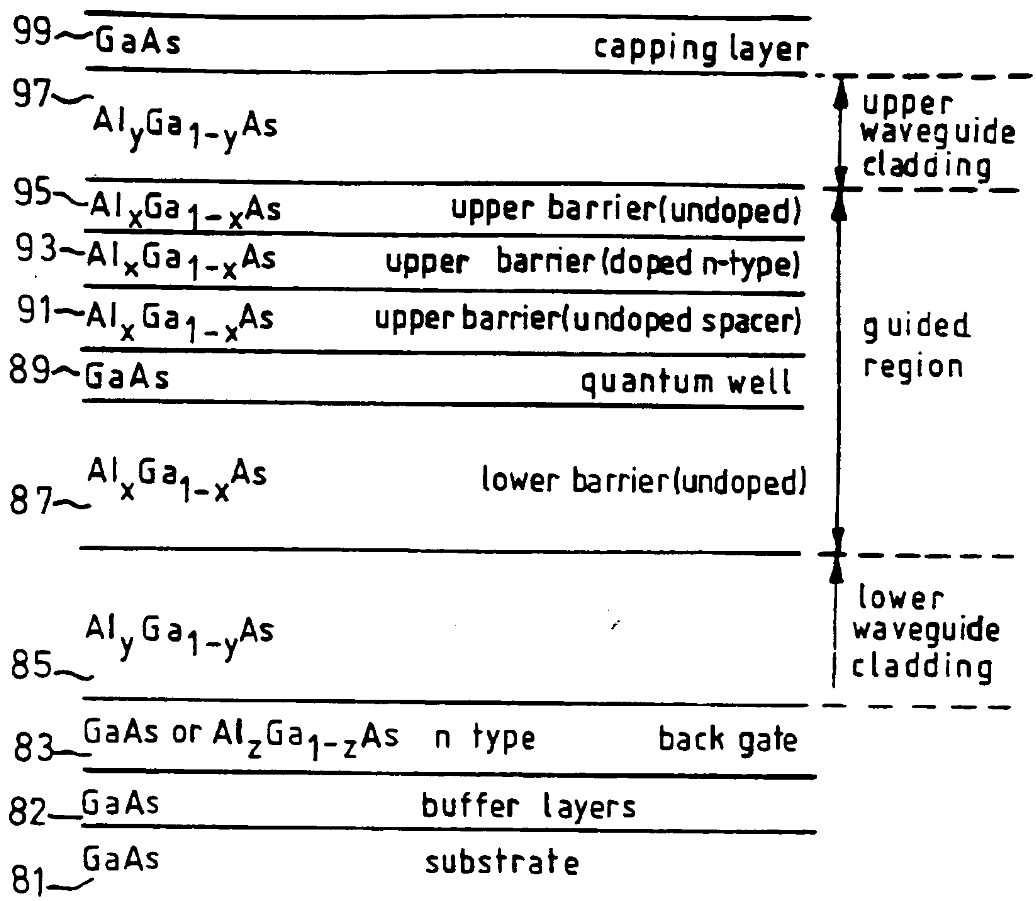

99 GaAs capping layer
97 $Al_yGa_{1-y}As$
upper waveguide cladding
95 $Al_xGa_{1-x}As$ upper barrier(undoped)
93 $Al_xGa_{1-x}As$ upper barrier (doped n-type)
91 $Al_xGa_{1-x}As$ upper barrier(undoped spacer)
89 GaAs quantum well
guided region
87 $Al_xGa_{1-x}As$ lower barrier(undoped)
85 $Al_yGa_{1-y}As$
lower waveguide cladding
83 GaAs or $Al_zGa_{1-z}As$ n type back gate
82 GaAs buffer layers
81 GaAs substrate

FIG.11a

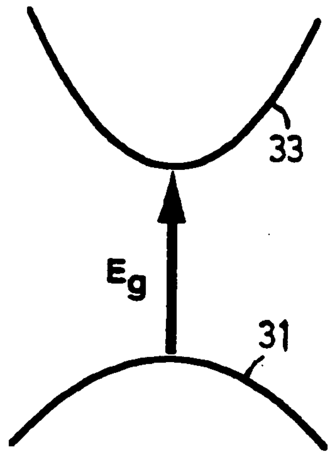


FIG 11b

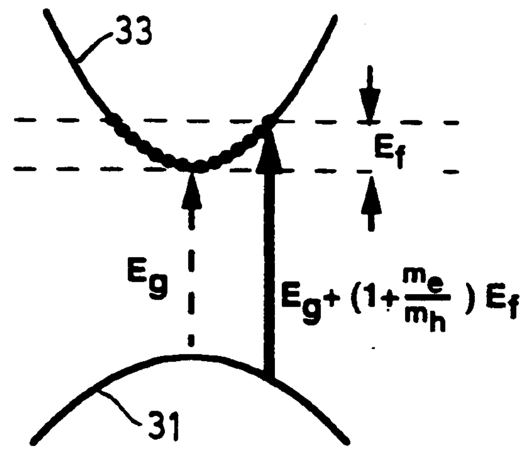
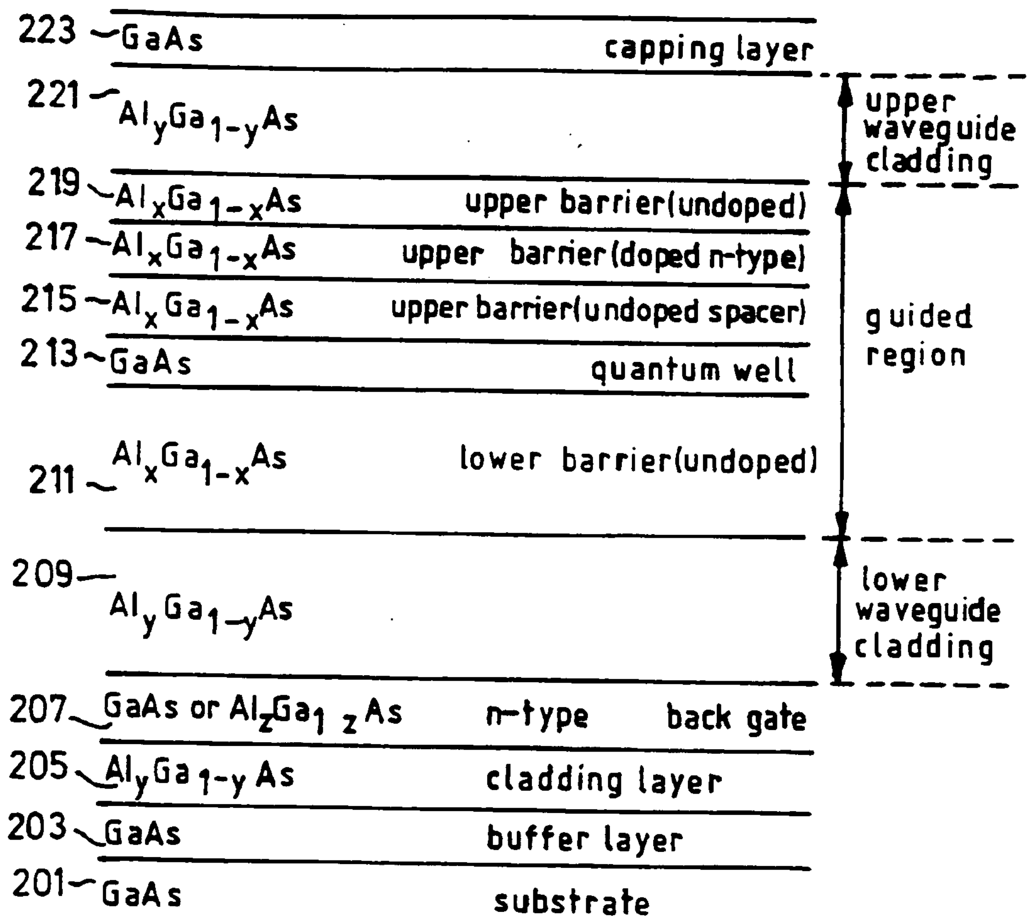


FIG. 12



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Optical Modulator

The present invention relates to an optical modulator. An electro-optical modulator is a device where the intensity of a transmitted optical beam is controlled by applied electrical signal(s). The applied electrical signal(s) can be switched between two values so as to modulate the intensity of the optical beam and hence encode information. It can be used as a discrete element or integrated into a larger electro-optical circuit. When combined with other elements the device can perform as an optical logic element. The modulator can also be used to control the intensity of an optical signal with electrical signals.

Optical modulators based on field effect transistor (FET) structures have been proposed previously in US 4 872 744. In the device disclosed in this document, the guided region comprises a quantum well, two ohmic contacts are provided to the guided region with a single Schottky gate being provided on the surface of the structure.

The single gate can be used to control the free carrier density within the quantum well. The absorption of an optical beam by a quantum well is dependent on the free carrier concentration within the well by the Moss Burstein effect. Adding carriers to the well blocks the band edge absorption, thereby increasing the absorption threshold energy to be close to the band-gap (E_g) plus the Fermi energy (E_f) of the carriers.

However, as discussed below, there is a flaw in the device disclosed in US 4 872 744 for this mode of operation, since the addition of excess carriers also leads to an undesirable reduction in the band-gap energy, E_g.

With a negligible excess carrier density in the quantum well, its absorption threshold, i.e. the minimum photon energy that can be absorbed, is close to the energy of the

band-gap (E_g) between the maximum of the valence band and the minimum of the conduction band.

The device disclosed in US 4 872 744 relies upon adding excess electrons to the quantum well in order to increase its absorption threshold. The added excess carriers fill the bottom of the conduction band up to the Fermi energy (E_f). Since photo-excitation of an electron from the valence band is only possible into an unoccupied conduction band state, this has the effect of blocking the absorption at photon energies close to the band-gap energy (E_g). The absorption threshold then lies to higher photon energy, close to (E_g + E_f). This blue-shifting of the absorption threshold with increasing carrier density is known as the Burstein-Moss effect. (For a quantum well whose band-gap is direct in k-space, the absorption threshold is actually a little larger than (E_g + E_f) by an amount equal to the valence band energy at the Fermi wavevector, since only transitions between valence and conduction band states with similar k-vector are allowed)

However, there is a flaw in the device disclosed in US 4 872 744 in this mode of operation, since adding excess carriers to the quantum well also causes considerable lowering of the band-gap energy (E_g), which partially cancels the increase in the absorption threshold due to the filling of the bottom of the conduction band. The reduction of the band-gap with excess carrier density has two sources: band-gap renormalisation and the quantum confined Stark effect (QCSE). The QCSE is caused by an electric field across the quantum well induced by excess charge added to the quantum well. This electric field polarises the electron and hole wavefunctions towards the opposite faces of the quantum well, while the confining barrier prevent their complete escape. The net result is a large shift of the band-gap to lower energies with increasing excess carrier density. This redshift of the band-gap is undesirable because it partially cancels the blueshift due to the Burstein-Moss effect.

The arguments presented above ignore the Coulombic attraction between electrons and holes. These are most significant when there is a negligible density of excess electrons in the quantum well. The photo-excited electron and the 'hole' which it leaves behind in

the valence band have a mutual attraction which results in them forming a bound state or 'exciton'. The binding effect of this exciton lowers the absorption threshold. Coloumbic effects are less important in the presence of excess carriers

The QCSE seriously degrades the performance of the optical modulator as it reduces the change in absorption between the opaque and transparent states. However, the applicants have found a method of suppressing the degrading effect of the QCSE in such a modulator.

Therefore, in a first aspect, the present invention relates to an optical modulator comprising a guided region for transmission of the optical beam therethrough, first and second gates, an ohmic contact to the guided region and a substrate, the guided region comprises a quantum well layer and the guided region is interspersed between the first and second gates.

For the avoidance of doubt as used herein, any reference to a layer overlying another will be taken to mean a layer which lies on the opposite side to the substrate of the layer which it overlies. Similarly, the terms above and below will be taken with reference to the substrate forming the base of the structure such that below means on the substrate side of a layer and above means on the opposite side of a layer to the substrate. The term region may refer to a single layer or a plurality of layers.

The complementary use of the first and second gates allows both the carrier concentration of the quantum well and the electric field across the quantum to be varied. This has many advantages. In a first instance, the ability to control the well shape and the carrier concentration within the well will allow more control over the absorption spectrum resulting in a greater contrast between the opaque and the transparent. The extra gate also allows the device to be tuned to work at a certain wavelength after fabrication.

For some modes of operation, it may be required to minimise the change in threshold absorption energy on changing the carrier concentration in the quantum well. This could easily be achieved in a device according to a first aspect of the present invention, as the first and second gates can be used to increase the field within the quantum well as well as decrease it.

The above description, has centred around device operation at the neutral exciton wavelength. When an electron is excited from the valence band to the empty conduction band, a hole is left behind in the valence band. The electron and hole form a bound pair, a neutral exciton. However, if the exciton is created in the vicinity of an excess electron, a negatively charged exciton may be formed, i.e. a bound state which consists of two electrons and a hole.

An optical modulator of this type may work at the wavelength of the neutral exciton, where adding carriers to the well suppresses the absorption or it may work at a charged exciton frequency, where depleting carriers from the well will suppress absorption. Whether the device is configured to work at the neutral exciton wavelength or the charged exciton wavelengths, the ability to alter the electric field across the quantum well as its electron density will enhance the device performances.

The modulator may also be configured for phase modulation of the incident beam, for this an incident beam energy of less than the band-gap is required.

For the device to operate with the light propagating in the plane of the quantum well, it is preferable to arrange the quantum well within a waveguiding structure. This is achieved by interspersing the central 'guided' region comprising the quantum well between 'cladding' layers of lower refractive index. For example, in a device according to the present invention fabricated using the GaAs/$Al_xGa_{1-x}As$ material system, this is achieved by composing the cladding layers of $Al_xGa_{1-x}As$ with a higher aluminium content than the guided region. For optimum optical mode, the guided region should have a total thickness of less than the wavelength of the light in the material.

Therefore, it is preferable if the modulator further comprises a first cladding layer. Such that the first cladding layer has a refractive index lower than that of the guided region. It may also be preferable for the modulator to comprises a second cladding layer with a refractive index lower than that of the guided region.

There are numerous ways of confining the light in a second direction, i.e. a direction in the plane of the layers. One well-known method is to form a 'stripe-loaded' waveguide where the upper cladding layer is arranged to be thicker in a stripe running along the length of the device. Optical confinement is achieved in the region under the stripe because the refractive index of the stripe is larger than that of the material or air lying on either side of the stripe.

Therefore, it is preferable if there is a variation in thickness in either or both of the first and/or second cladding layer so that the optical mode is confined to a predefined area of the guided region.

The optical mode, centred in the guided region, penetrates into the upper cladding region and as a result experiences a slightly larger refractive index in the region under the stripe. This has the effect of confining the light to the guided region under the stripe.

An optical modulator according to the present invention works by the ability to change the carrier concentration in the quantum well layer and the electric field across the quantum well. A convenient method for providing carriers to the quantum well layer is by means of doped layer. It is preferable if this is a doped barrier layer adjacent the quantum well layer. It is more preferable if this is a modulation doped barrier layer comprising a doped layer adjacent an undoped layer.

A field effect transistor with a single gate will not allow the control over the shape of the quantum well that a double gated structure will allow. However, the applicants have

found that it is still possible to minimise the reduction of the band-gap with increasing carrier concentration, in a single-gated structure with a doped layer, if the doped layer lies on an opposite side of the quantum well layer than the gate. Therefore, in a second aspect the present invention relates to an optical modulator comprising, a guided region for the transmission of an optical beam therethrough, a gate and an ohmic contact to said guided region, the guided region further comprising a doped layer and a quantum well layer, wherein the doped layer lies on an opposing side of the quantum well layer to the gate. In this case, addition of electrons from the doped layer to the quantum well layer will reduce the average electric field across the quantum well. The single gate may conveniently be either a front gate or a back-gate as discussed below for the double gated structure.

Returning to the double gated structure, a particularly convenient arrangement of the first and second gates is possible if the first gate is provided on an upper surface of said modulator and the second gate is a back-gate provided on a substrate side of the guided region.

The front-gate is formed overlying the modulator. Therefore, the front gate may be conveniently comprise a metallic layer. The front gate may also comprise either in addition to or instead of the metallic layer a highly doped semiconductor layer. It is convenient to arrange the first gate on top of the stripe region.

From a fabrication point of view it is preferable if the back-gate comprises a highly doped semiconductor material. However, the back-gate may also comprise a metallic layer either in addition to or instead of the highly doped semiconductor layer. This metallic layer may be formed on a back surface of the substrate. Part of the substrate could also be thinned before evaporation of the metallic layer.

There are problems with incorporating a back-gate into a device where ohmic contact is required to layers which lie above the back-gate. The ohmic contacts to the *guided* region may penetrate deep into the sample and contact the back-gate. This problem can

be circumvented by a number of methods. Shallow ohmic contacts may be used, for example, PdGe, which do not penetrate so far into the sample. Other methods for overcoming these problems involve patterning the back-gate.

To clarify the terminology, a patterned layer, is a layer which there is some variation in the properties of that layer in a direction perpendicular to the direction of formation of that layer. For example, there could be a variation in the conductivity of that layer, or the thickness of the layer. Ion beam damage or ion beam implantation, to vary the conductivity within the back-gate layer. Ion beam damage could be used on an n^- layer to destroy the conductivity in the regions where the back-gate lies under the ohmics. Alternatively, the back-gate could be undoped and dopants could be implanted in the sections where conduction is required. The contact to the back-gate could be made well away from the guided region of the device.

A particularly convenient way of patterning the back-gate is provided by etching. The back-gate may be patterned so that there is a variation in the thickness of said gate or that the gate only occupies the region underneath the guided region and a region where contact to it is required.

The problem which arises when etching a device for further layers to be regrown is that the surface of the device which is to be regrown on should preferably not have any steps on it. It is therefore advantageous if the back-gate comprises oblique facets.

A second advantage of patterning the back-gate, is that if the back-gate has a higher refractive index than that of the other layer(s) situated on the substrate side of the lateral confinement region, it will also act as an inverted stripe loaded layer. The optical mode will then be confined to part of the guided region above the back-gate, since it experiences a larger refractive index in this region.

Therefore, it is preferable if the back-gate has a refractive index higher than that of the other layer(s) situated on the substrate side of the lateral confinement region.

To take advantage of this feature, the lower cladding layer formed overlying the back-gate should be sufficiently thin so that the optical mode has some (small) amplitude in the back-gate region. Additional waveguiding could be provided by etching the upper cladding layer to form a thicker stripe region above the back-gate.

The above method of using the patterned back-gate layer to act as both a means for controlling the carrier concentration in the guided region and a means for confining the optical mode present considerable advantages for the fabrication of optical modulators and should not only be limited to modulators operating in accordance with the Moss Burstein effect. It will also provide advantages for optical modulators based on p-i-n structures where the modulators comprise a first and a second terminal where the first and second terminal comprises highly doped layers of opposing conductivity types.

Thus in a third aspect the present invention relates to an optical modulator comprising a semiconductor substrate, a guided region for transmission of an optical beam therethrough and a lateral confinement region, the lateral confinement region is situated on the substrate side of the guided region, there is a variation in the thickness of said lateral confinement region so that an optical mode in said guided region is confined to a predetermined region of the guided region.

The lateral confinement region is a layer or plurality of layer which is used to confine the optical mode in a predefined region of the guided region. For example, the lateral confinement region could act as an inverted stripe loaded layer wherein the lateral confinement region has a different refractive index than that of a layer situated on the substrate side of the lateral confinement region. For this mode of operation it would be preferable if the lateral confinement region had a refractive index higher than that of the layer(s) situated on the substrate side of the lateral confinement region.

However, for confinement of the optical mode it is not a requirement that the optical confinement region has a different refractive index to that of a specified layer. The

change in the relief of the guided region formed overlying the lateral confinement region should result in the in the confinement of the optical mode to a predefined area of the guided region. Furthermore, the growth rate of the layer which form the guided region on the non-planar region should be slower than that on the planar regions. Therefore the layers which form the guided region should in general be thicker on planar regions than on the non planar regions which will also produce lateral optical confinement. A planar region is defined as a layer or plurality of layers formed with the same plane as that of the substrate. Similarly, a non-planar region is defined as a layer or plurality of layers which are not parallel to the substrate plane.

The lateral confinement region may conveniently be a gate or a terminal. Thus, it may be preferable if the guided region of a device according to a third aspect of the present invention may comprises a single quantum well layer or a plurality of quantum well layers.

The modulator will be described with reference to the GaAs/$Al_xGa_{1-x}As$ material system. However, it should not be limited to this. Many material systems could be used, for example: InGaAs/AlGaAs, InGaAs/InP, GaInP/(AlGa)InP, ZnCdSe/ZnSe, ZnSe/ZnMgSSe, ZnCdSe/ZnSSe, CdTe/CdZnTe, GaN/AlN, GaN/AlGaN, InGaN/GaN, InGaN/AlGaN and Si/SiGe.

When choosing a material system it is preferable if the material of the quantum well layer possess a direct band-gap.

The present invention will now be explained in more detail by reference of the following non-limiting preferred embodiments and with reference to the accompanying drawings, in which:

Figure 1 shows single gated field effect transistor structures which may be used as an optical modulator;

Figure 2 is a selection of double gated field effect transistor structures in accordance with a first aspect of the present invention, which may be used as optical modulators;

Figure 3 is a graph of photon energy against electron density for an optical modulator based on a single gated field effect transistor;

Figure 4 is a graph of photon energy against electron density for an optical modulator in accordance with a first aspect of the present invention;

Figure 5 is a band profile of a single gated field effect transistor when used as an optical modulator in the state with finite carrier density in the quantum well;

Figure 6 is a band profile of an optical modulator in accordance with a first aspect of the present invention, in the state with finite carrier density in the quantum well;

Figure 7 is an optical modulator in accordance with a first aspect of the present invention, where contact to the guided region is made by shallow ohmic contacts;

Figure 8 is a detail of the guided region in accordance with the present invention;

Figure 9 is an optical modulator in accordance with a first and third aspect of the present invention, with a patterned back gate;

Figure 10 is a possible layer structure for the optical modulator in accordance with a first aspect of the present invention as shown in Figure 7;

Figure 11 is a schematic band structure to show the Moss Burstein effect; and

Figure 12 is a possible layer structure for an optical modulator in accordance with a first and third aspect of the present invention.

Figure 1a shows variations of a single gate field effect transistor in which the carrier concentration in the quantum well may be altered. The quantum well 7, is formed overlying the substrate 1. The upper dopant layer 9, is formed overlying the quantum well layer 7 and the front gate 11, is formed overlying the upper dopant layer 9. By applying a voltage between the front gate 11 and an ohmic contact to the quantum well (not shown), the number of carriers induced in the quantum well 7 from the upper dopant layer 9, can be varied. The possible variations on this structure are shown in figures 1b to 1f. Figure 1b shows the reverse structure to 1a, where the carrier concentration in the quantum well 7, is changed by a voltage applied to the back gate 3. It can be seen here that a lower dopant layer 5, lies between the gate and the quantum well 7.

Figure 1c and 1d show a field effect transistor according to a second aspect of the present invention where the dopant layer is on an opposing side of the quantum well layer to the gate. In 1c, the lower dopant layer 5 is formed overlying in the substrate 1. The quantum well layer 7, is formed overlying the lower dopant layer 5, and the front gate 11, is formed overlying the quantum well 7. In 1d the back gate 3 is formed overlying in the substrate 1. The quantum well layer 7, is formed overlying the back gate 3 and the upper dopant layer 9 is formed overlying the quantum well. Figures 1e and 1f show a field effect transistor structure with dopant layers formed on either side of the quantum well layer 7. Figure 1e shows a structure with a front gate 11, figure f shows a structure with a back-gate 3.

Figure 2 shows optical modulators in accordance with a first aspect of the present invention where both a front and a back gate are provided. Figure 2a is similar to figure 1a. However, a back gate 3 is provided overlying the substrate 1. In figure 2b, the carriers to the quantum well are provided by a lower dopant layer 5. In figure 2c both upper 9 and lower 5 doping layers are shown.

Figure 11 shows the principles of operation behind an optical modulator working on the Moss Burstein principle. Figure 11a shows a schematic band diagram of the conduction

valence bands. Upon illumination electrons are excited from the valence band 31 to the conduction band 33. If the conduction band 33 already has some carriers as shown in figure 11b, the energy required to excite an electron into the conduction band 33 from the valence band 31 is close to the sum of the band gap (E_g) plus the Fermi energy (E_f). The Fermi energy is a level which the electrons fill up to in the conduction band 33. This is the Moss Burstein principle, where the band edge absorption as shown in figure 11a is suppressed due to the conduction band edge states already being occupied by excess electrons. However, optical modulators that work on this principle suffer from the problem that although the energy required to excite an electron is the band gap plus the Fermi energy, the band in figure 11b is smaller than that shown in figure 11a. The reason for this will now be explained with reference to figure 5.

Figure 5 shows results from a calculation of the conduction and valence band edges around the quantum well of a single gated device, in addition to the wavefunction of the lowest electron 25 and hole 27 levels. The band profiles are shown for the state of the modulator where there is a large electron density in the quantum well 21. The electron charge in the quantum well 21 creates a non-uniform electric field across the quantum well. This is apparent in Figure 5 with the sloping of the conduction and valence bands within the quantum well. This electric field polarises the electron wavefunction 25 towards the left hand side and the hole 27 wavefunction towards the right-hand side of the quantum well 21. The spatial separation of the electrons and holes reduces the energy separation of their energy levels, i.e. the band-gap, due to the quantum confined Stark effect.

Figure 6 shows the band profile of an optical modulator working in accordance with the present invention. Here, a back-gate bias is applied, so as to reduce the average electric field across the quantum well in the state where there is a large electron density in the quantum well. Hence, the electric field resulting from the bias applied to the back-gate opposes the electric field 23 induced by the electron charge added to the well. In this case, the maximum of the electron 25 and hole 27 wavefunctions are closer to the centre

of the plane of the quantum well 21 and hence the undesirable, charge-induced redshift of the band-gap is reduced.

A calculation of the variation in the band gap with the electron density and the variation of the band-gap plus the Fermi energy, in both the single gated case and the double gated case is shown in figures 3 and 4. Figure 3 shows the dependence for a single gated device. The sharp decrease of the band gap energy (Eg) with electron density can be seen readily. As a consequence, the absorption threshold, i.e. the minimum photon energy for optical absorption (which lies close to the Fermi Energy plus the band-gap (Eg + Ef)), increases much less rapidly than anticipated by band filing arguments alone. This contrasts to the characteristics of the double gated device shown in figure 4. Here, the decrease of the band gap with electron density is greatly suppressed and indeed shows an increase at the lowest electron densities when compared to that of figure 3 and hence, the absorption threshold increases more sharply with electron density. The much larger modulation of the absorption threshold energy facilitated by the double gated device, will result in much improved contrast ration between the transparent and opaque states.

The results of the calculations shown in figures 3 to 6 were calculated using a self consistent solution of the coupled Poisson-Schrodinger equations for a typical structure. For the simulations the guided region comprised (in order of growth, i.e. first layer is on the substrate side).

160 nm	undoped	$Al_{0.33}Ga_{0.67}As$;
30 nm	undoped	GaAs quantum well;
20 nm	undoped	$Al_{0.33}Ga_{0.67}As$ spacer layer;
40 nm	n-type doped ($3.5x10^{17}cm^{-3}$)	$Al_{0.33}Ga_{0.67}As$;
100 nm	undoped	$Al_{0.33}Ga_{0.67}As$

A possible arrangement for the device is shown in figure 7. Here a back gate 53 is formed on the surface of a semiconductor substrate (not shown). A lower cladding

layer 55 is then formed on an upper surface of the back gate 53. Alternatively, a doped substrate can be used to act as a back-gate itself. The guided region 57 is then formed on an upper surface of the lower cladding layer 55. The upper cladding layer 59 is then formed on an upper surface of the guided region 57. The two cladding regions 55 and 59 possess a lower refractive index than the guided region 57. Therefore, the optical mode can be confined to the guided region 57. The upper cladding layer 59, is patterned from a ridge structure. Due to the variation in thickness of the layer, the optical mode is confined directly underneath the thicker part of layer 59. A front Schottky gate 61 is then formed on an upper surface of the upper cladding layer 59. It is preferable if the front Schottky gate 61 is formed on the surface of the thicker part of the upper cladding layer 59, as shown here. Shallow ohmic contacts 63 and 65 are then made to the guided region 57. Contact may be made to the back gate 53 by an ohmic contact 67. Alternatively, contact to the back-gate can be made via the lower surface of the substrate, if a doped substrate is employed. The ohmic contact 67 does not make contact to the guided region, as this layer is etched away before the contact is evaporated, as shown in the diagram.

Figure 8 shows details of the guided region. A quantum well layer 73 is formed on top of a lower barrier layer 71. An undoped spacer layer 75 is then formed on an upper surface of the quantum well layer 73. A doped upper barrier layer 77 is then formed on the surface of the undoped spacer layer 75. A second undoped spacer layer 79 is then formed on the upper surface of the doped upper barrier layer 77. The undoped spacer layer 75 separates the carriers in the quantum well 73 from the dopants in the upper barrier 77. This increases the mobility of the carriers in the quantum well 73, which will increase the optical switching time of the device.

Figure 9 shows an interesting variant on the present invention. The device is very similar in structure to that shown in figure 7. However, here the back gate is patterned. An undoped buffer layer 52 is formed on the surface of the substrate 51, back gate layer 53 is then formed on an upper surface of the undoped buffer layer. The growth is then stopped and the back gate 53 is etched to produce the patterned back gate which with

oblique facets 101. The etched structure is then re-grown with a lower cladding layer 55, on the upper surface of the back gate 53 and the undoped buffer layer 52. The guided region 57 is then formed on an upper surface of the lower cladding layer 55. The upper cladding layer 59 is then formed on an upper surface of the guided region 57. The front gate 61, is then formed on an upper surface of the upper cladding layer 59. The two cladding layers have a lower refractive index than the guided region 57, so as to provide optical confinement. The back-gate layer 53, has a higher refractive index than buffer layer 52, so as to provide lateral optical confinement. Optionally, the upper cladding layer can be patterned to form a layer with a varying thickness to provide additional lateral optical confinement.

This idea of using the back gate as a part of the cladding layers and to confine the optical mode to a predetermined region of the guided region 57 has advantages for any optical structure where confinement of the optical mode is required. The operation of this should not just be limited to devices which work on the Moss Burstein effect. However, for the structure shown in Figure 9, there are some design considerations which must be taken into account. It is important, that the doping of the layers formed overlying the oblique facets 101, is not too heavily compensated. Otherwise the situation might arise where the quantum well in the facet regions is intrinsic or the well might contain carriers of the opposite polarity to the quantum well formed on the planar regions. This can be avoided by careful selection of the growth parameters and/or the facet etch angle.

Figure 10 shows a layer structure for a device according to the present invention as shown in Figure 7, fabricated using the GaAs/$Al_xGa_{1-x}As$ material system. Here, the substrate 81 and buffer layers 82 are undoped GaAs. The back gate can be either formed from n type GaAs or $Al_zGa_{1-z}As$ 83. The lower cladding layer may be fabricated from undoped $Al_yGa_{1-y}As$ 85. The guided region may be formed from a plurality of layers. Starting with a lower barrier layer which is formed from $Al_xGa_{1-x}As$ 87 ($x<y$) a quantum well layer 89 which is formed from undoped GaAs. An upper barrier layer which is formed from an undoped AlGaAs spacer layer 91 a doped barrier

layer which is $Al_xGa_{1-x}As$ 93 and an undoped $Al_xGa_{1-x}As$ upper spacer layer 95. The upper cladding layer may be conveniently formed from $Al_yGa_{1-y}As$ 97 and the structure may be finished with a GaAs layer 99. It is on this layer that the front gate may be formed.

Figure 12 shows a possible layer structure for the device shown in Figure 9, fabricated using the GaAs/$Al_xGa_{1-x}As$ material system. Here, the substrate is undoped GaAs 201. Optionally GaAs buffer layers 203 may be formed on an upper surface of the substrate 201. Then and $Al_yGa_{1-y}As$ cladding layer 205 is formed, the refractive index of this layer is lower than that of the back-gate 207 which is formed on an upper surface of this cladding layer 205. The back gate can be either formed from n type GaAs or $Al_zGa_{1-z}As$ 207, where $z<y$. The growth is then stopped and the back-gate layer 207 is etched down to the substrate cladding layer 205 to form a patterned back-gate. To ensure the smooth growth of subsequently grown layers, the gate is etched to expose sloping sidewalls as shown in Figure 8. This can be conveniently achieved using a hydrogen peroxide/buffered hydrofluoric acid based etch. The gate is patterned so that a portion of the gate extends away from the active region of the device so that ohmic contact can be made to the back-gate. The lower cladding layer may be fabricated from undoped $Al_yGa_{1-y}As$ 209. This is formed on an upper surface on the back-gate 207 and the substrate cladding layer 205, so that the back-gate 205 is surrounded by cladding layers. The guided region may be formed from a plurality of layers. Starting with a lower barrier layer which is formed from $Al_xGa_{1-x}As$ 211 ($x<y$) a quantum well layer 213 which is formed from undoped GaAs. An upper barrier layer which is formed from an undoped AlGaAs spacer layer 215 a doped barrier layer which is $Al_xGa_{1-x}As$ 217 and an undoped $Al_xGa_{1-x}As$ upper spacer layer 219. The upper cladding layer may be conveniently formed from $Al_yGa_{1-y}As$ 221 and the structure may be finished with a GaAs layer 223. It is on this layer that the front gate may be formed.

In the light of this disclosure, modifications of the described embodiment, as well as other embodiments, all within the scope of the present invention as defined by the appended claims, will now become apparent to the person skilled in the art.

CLAIMS:

1. An optical modulator comprising a guided region for transmission of an optical beam therethrough, first and second gates, an ohmic contact to said guided region and a substrate, wherein the guided region comprises a quantum well layer and the guided region is interspersed between the first and second gates.

2. An optical modulator comprising a guided region for the transmission of an optical beam therethrough, a first gate and an ohmic contact to said guided region, the guided region further comprising a doped layer and a quantum well layer, wherein the doped layer lies on an opposing side of the quantum well layer to the first gate.

3. An optical modulator according to any preceding claim wherein, the ohmic contact is a shallow ohmic contact.

4. An optical modulator according to either of claims 1 and 3, wherein said second gate comprises regions of different conductivity types.

5. An optical modulator according to any preceding claim, wherein the said first gate comprises a highly doped semiconductor layer.

6. An optical modulator according to any preceding claim, wherein the said first gate comprises a metallic layer.

7. An optical modulator according to any of claims 1, 3 to 6, wherein the said second gate comprises a highly doped semiconductor layer.

8. An optical modulator according to any of claims, 1, 3 to 7 wherein the said second gate comprises a metallic layer.

9. An optical modulator according to any of claims 1,3 to 8, wherein the first gate is provided on an upper surface of said modulator and the second gate is a back-gate provided on a substrate side of the guided region.

10. An optical modulator according to claim 2, wherein the first gate is a back-gate provided on a substrate side of the device.

11. An optical modulator according to claim 2, wherein the first gate is a surface gate provided on an upper surface of the device.

12. An optical modulator according to either of claims 9 and 10, where there is a variation in the thickness of said back-gate.

13. An optical modulator according to claim 12, wherein said back gate comprises oblique facets.

14. An optical modulator according to either of claims 11 and 12, where the refractive index of said back-gate is higher than that of a layer interspersed between the back-gate and the guided region.

15. An optical modulator according to claim 14, wherein the layer formed on an upper surface of said back-gate is sufficiently thin to allow the optical mode to penetrate through it into the back-gate.

16. An optical modulator according to any of claims 1, 3 to 9 and 12 to 15 when not dependent on claim 2, wherein the guided region further comprises a doped layer.

17. An optical modulator according to any of claims 2, 10, 11 and 16, wherein the doped layer is a modulation doped layer comprising a doped layer adjacent an undoped layer.

18. An optical modulator according to any preceding claim, wherein the modulator further comprises a first cladding layer, such that the first cladding layer has a refractive index lower than that of said guided region.

19. An optical modulator according to claim 18, wherein the modulator further comprises a second cladding layer, such that the second cladding layer has a refractive index lower than that of said quantum well layer.

20. An optical modulator according to either of claims 18 and 19, where there is a variation in the thickness of the first cladding layer such that an optical mode is confined to a predefined area of the guided region.

21. An optical modulator according to any preceding claim, wherein the modulator is configures to work at the neutral exciton frequency.

22. An optical modulator according to any preceding claim , wherein the modulator is configured to work at a charged exciton frequency.

23. An optical modulator according to any preceding claim, wherein the modulator is configured to modulate the phase of an incident beam.

24. An optical modulator comprising a semiconductor substrate, a guided region for transmission of an optical beam therethrough and a lateral confinement region, the lateral confinement region is situated on the substrate side of the guided region, there is a variation in the thickness of said lateral confinement region so that an optical mode in said guided region is confined to a predetermined region of the guided region.

25. An optical modulator according to claim 24, wherein the lateral confinement region has a different refractive index than that of a layer on the substrate side of the lateral confinement region.

26. An optical modulator according to claim 25, wherein the lateral confinement region has a higher refractive index than that of a layer on the substrate side of the lateral confinement region.

27. An optical modulator according to any of claims 24 to 26, wherein the lateral confinement region comprises a gate.

28. An optical modulator according to any of claims 24 to 26, wherein the lateral confinement region is a first terminal and the modulator further comprises a second terminal, such that the first and second terminals are of opposing conductivity types.

29. An optical modulator according to any of claims 24 to 28, wherein the guided region comprises a quantum well.

30. An optical modulator according to any of claims 24 to 28, wherein the guided region further comprises two or more quantum wells.

31. An optical modulator according to any preceding claim, wherein the quantum well layer possess a direct band-gap.

32. An optical modulator substantially as hereinbefore described with reference to any of the accompanying diagrams.

The Patent Office

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Application No: GB 9621073.7
Claims searched: 1

Examiner: SJ Morgan
Date of search: 20 December 1996

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.O): H1K(KFXL,KFN); G2F(FCE,FCW)

Int Cl (Ed.6): G02F

Other: Online:WPI,JAPIO,INSPEC

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
X	EP 0 645 858 A2	(CANON) See lines 20-23, page 5 in particular.	1,3,5-9, 18,19, & 21-23.
X	EP 0 460 793 A1	(AT&T) See line 9, page 3 - line3, page 4.	1,3,5-9, 12,18,19 & 21-23.
X	US 5 329 137	(USAF) See whole document.	1,3,5-9, 12,18,19 & 21-23.

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
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